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Two-fluid three-field peeling-ballooning mode simulation in snowflake divertor geometry using BOUT++

Jingfei Ma

In collaboration with

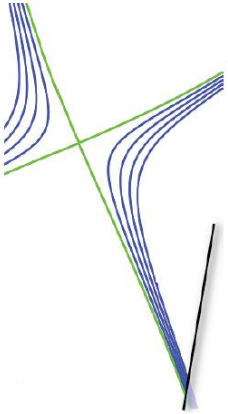
X. Q. Xu, D. D. Ryutov, M. V. Umansky and B. D. Dudson

Outlines

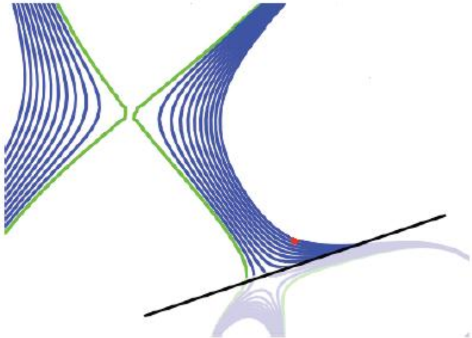
- Introduction.
- Equilibrium and Two-fluid three-field peeling-ballooning model.
- Linear simulation results and analysis.
- Conclusion and future work.

Advanced divertor concepts

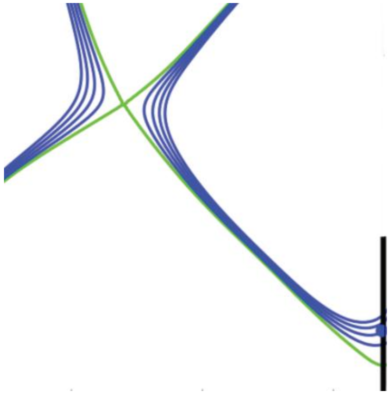
Divertor concept was first realized on ASDEX, Germany.



X-divertor, 2004, M. Kotschenreuther, P. M. Valanju, S. M. Mahajan et al.



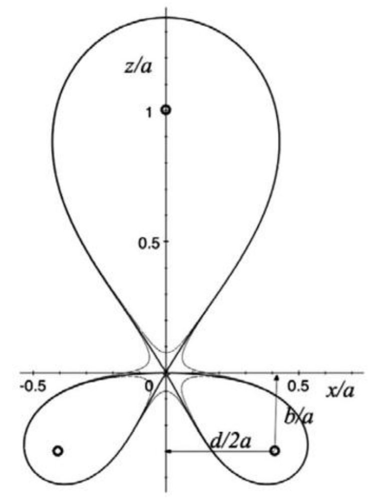
Super X-divertor, 2007,
M. Kotschenreuther,
P. M. Valanju, S. M. Mahajan et al.



M.Kotschenreuther, PPPL report, June 2013.

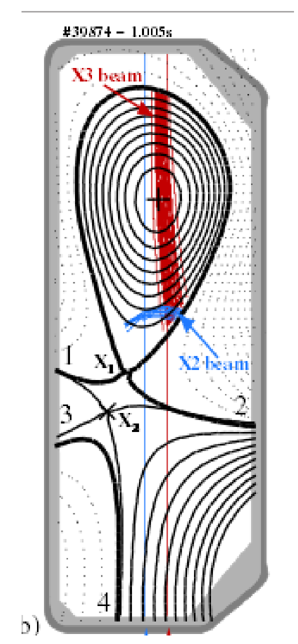
Advanced divertor concepts

Snowflake divertor, 2007, D.D.Ryutov

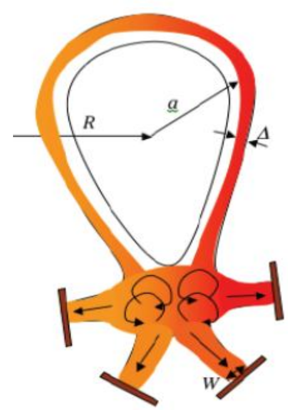


Advantages

- Reduce heat load on divertor plates by drawing particle flux to two additional legs. Verified by TCV experiment. (F. Piras et al. 2010)
- Enhance particle convection around x point by introducing second-order poloidal magnetic field.



How will the implementation of snowflake divertor change edge instabilities (ballooning mode) and ELM Bursts by altering pedestal characteristics?



D.D.Ryutov et al. 2007,2008.

Physics model for edge peeling-ballooning mode

Two-fluid three-field model

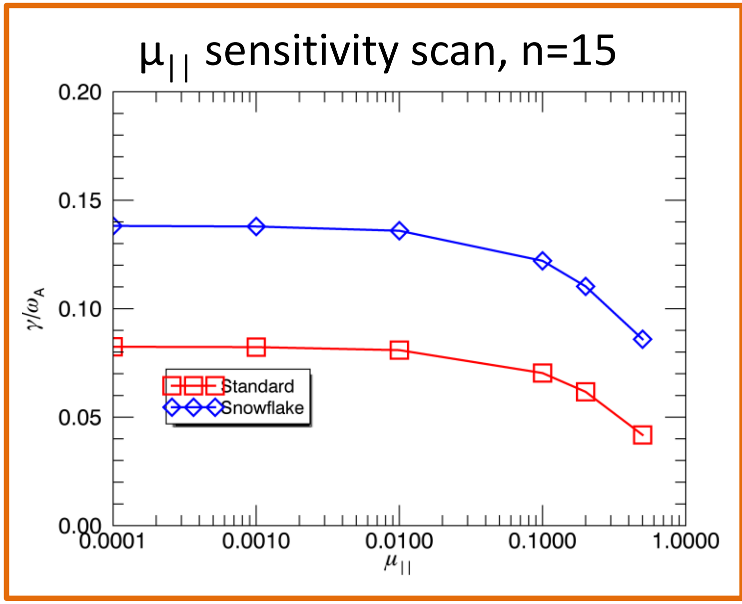
$$\frac{d\tilde{\varpi}}{dt} + \frac{1}{B_0}[\tilde{\phi}, \tilde{\varpi}] = B_0 \nabla_{\|0} \tilde{J}_\| + [\tilde{J}_\|, \tilde{A}_\|] + 2\boldsymbol{b_o} \times \boldsymbol{\kappa_o} \cdot \nabla \tilde{p} + \mu_{i,\|} \partial^2_{\|0} \tilde{\varpi}$$

$$\frac{d\tilde{p}}{dt} + \boldsymbol{V_{E_1}} \cdot \nabla P_0 + \frac{1}{B_0}[\tilde{\phi}, \tilde{p}] + 2\beta(\boldsymbol{b_o} \times \boldsymbol{\kappa_o}) \cdot \nabla \tilde{\phi} = 0$$

$$\frac{\partial \tilde{A}_\|}{\partial t} = -\nabla_{\|0} \Phi - [\tilde{\phi}, \tilde{A}_\|]$$

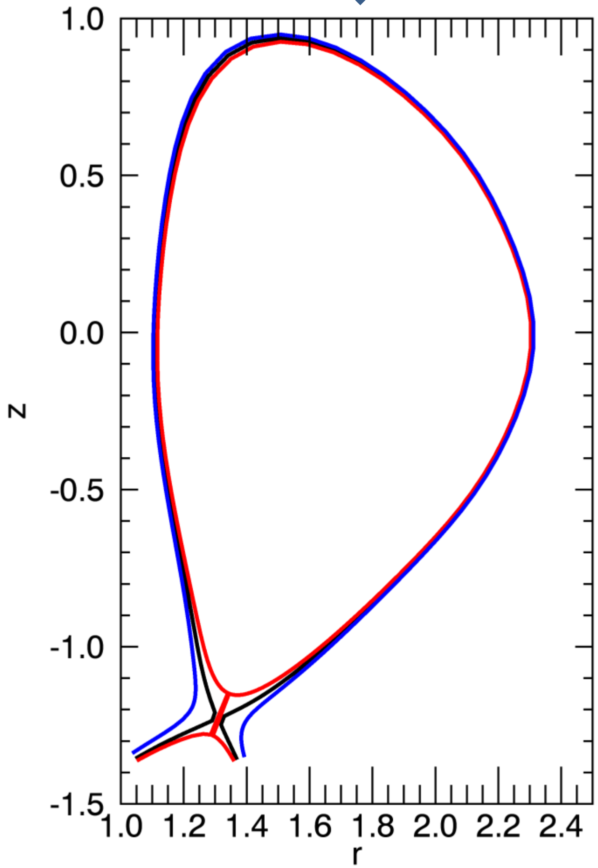
$$\varpi = \frac{n_0 M_i}{B_0} \left(\nabla_\perp^2 \tilde{\phi} + \frac{1}{n_0 Z_i e} \nabla_\perp^2 \tilde{p_i} \right), \Phi = \Phi_0 + \tilde{\phi}, P = P_0 + \tilde{p}$$

$$J_\| = J_{\|0} + \tilde{J}_\|, \tilde{J}_\| = -\frac{1}{\mu_0} \nabla_\perp^2 \tilde{A}_\|, \boldsymbol{V_{E_1}} = \frac{1}{B_0}(\boldsymbol{b_o} \times \nabla_\perp \tilde{\phi})$$



- For linear simulations, nonlinear terms in Poisson bracket will be disregarded.
- Parallel viscosity $\mu_{||}$ is set 0.1 for numerical convergence. This term affects growth rate by less than 10%.

Standard Divertor .V.S. Snowflake Divertor



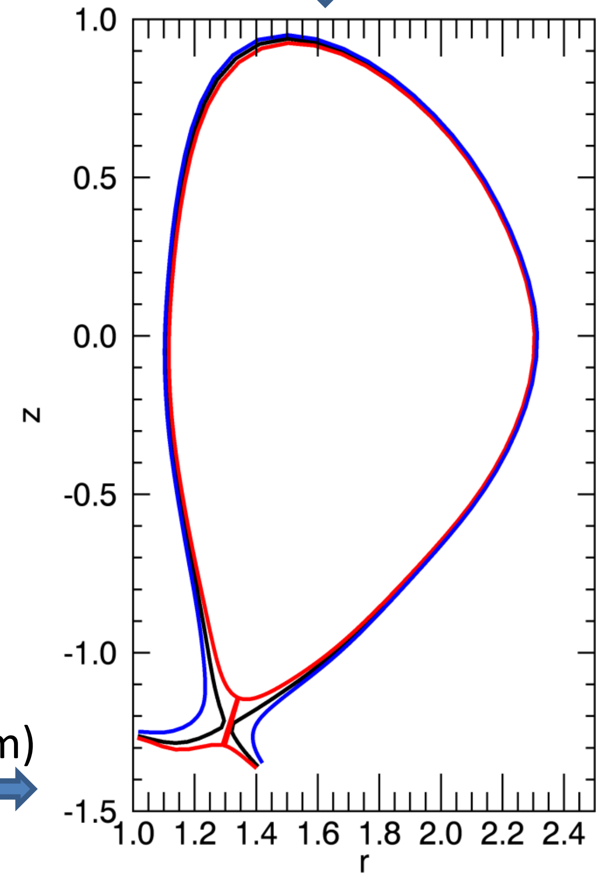
Standard Divertor Geometry

DIII-D

Shot number:

146394

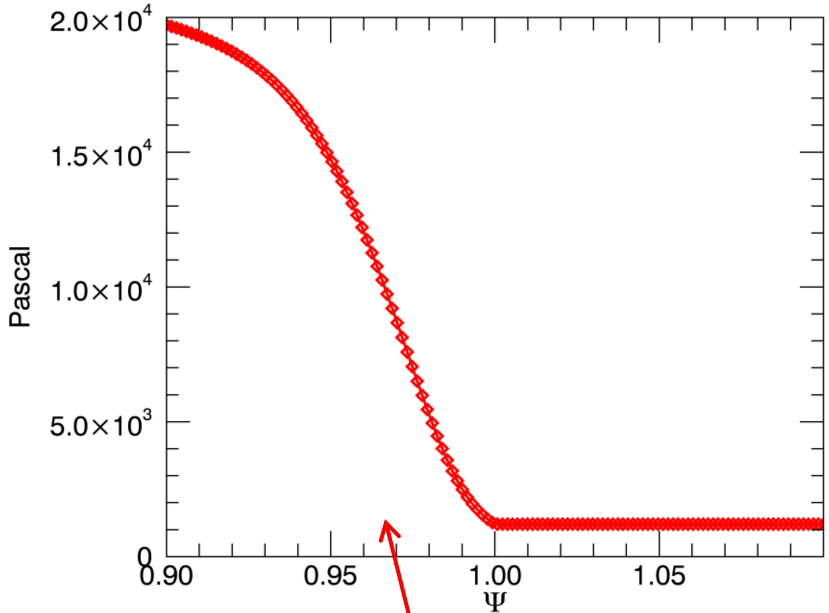
CORSICA (x-dist=25cm)

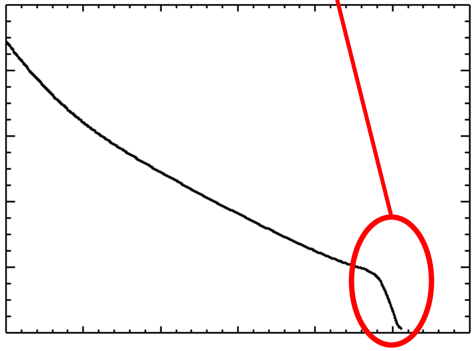


Snowflake (Plus) Divertor Geometry

Pressure and current profile

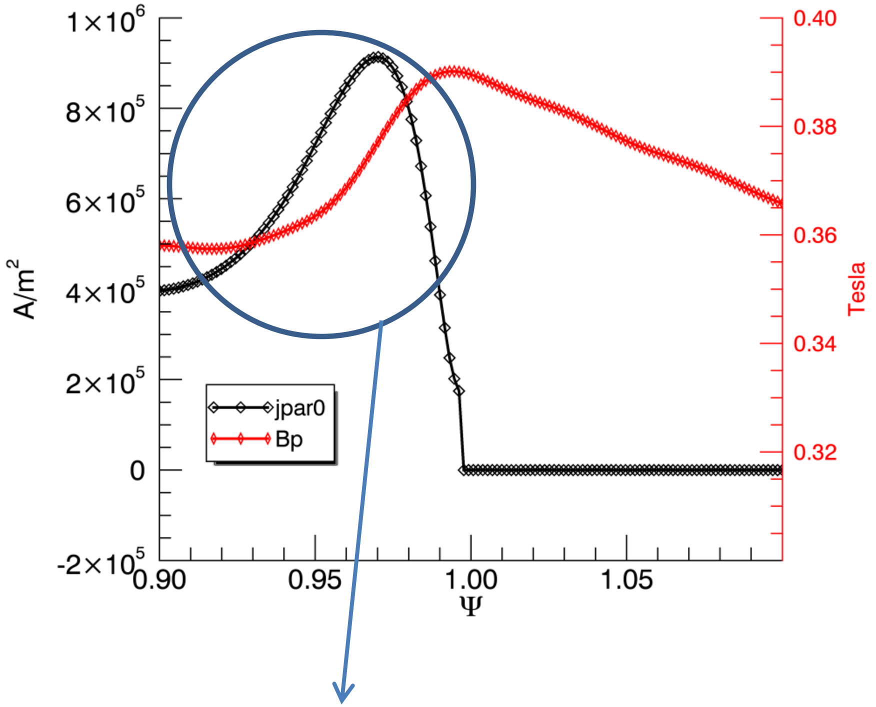
Pressure Radial Profile





Pedestal

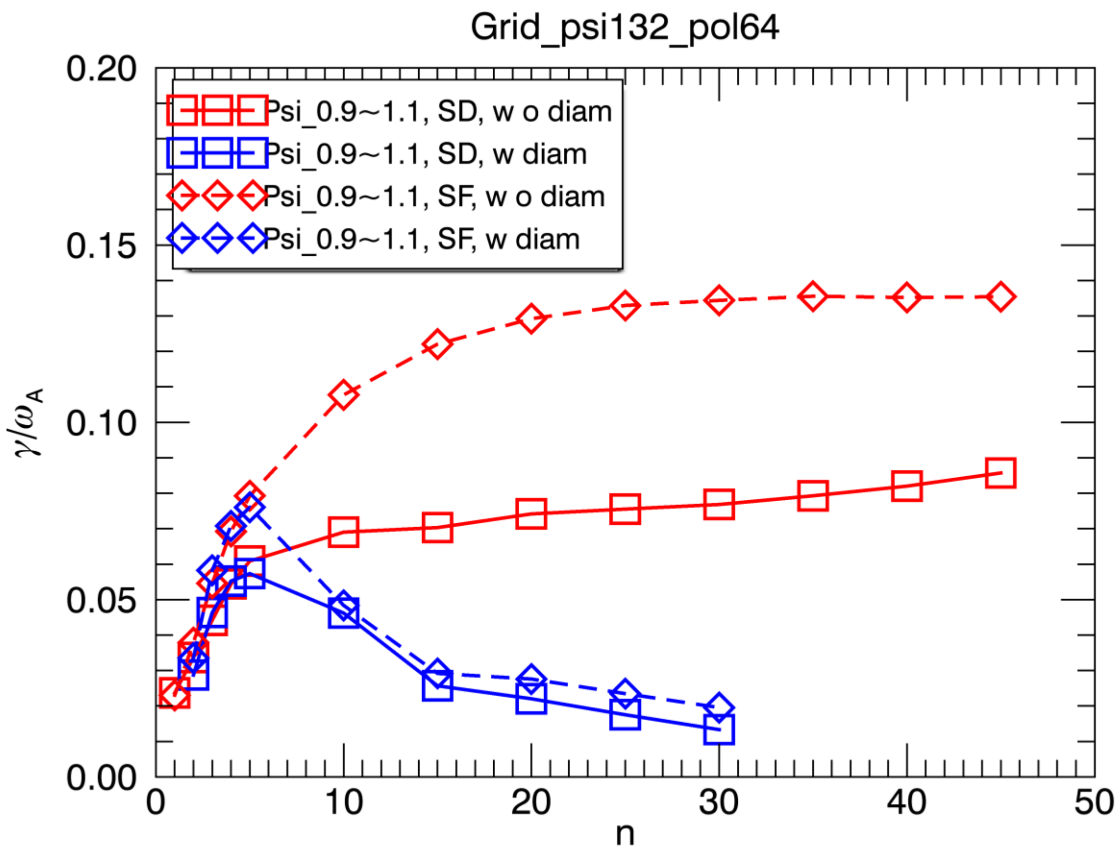
Parallel edge current profile (Magnetic surface averaged) and edge poloidal magnetic field.



Poloidal magnetic field increases rapidly in the edge due to edge current.

Linear results (Growth rate)

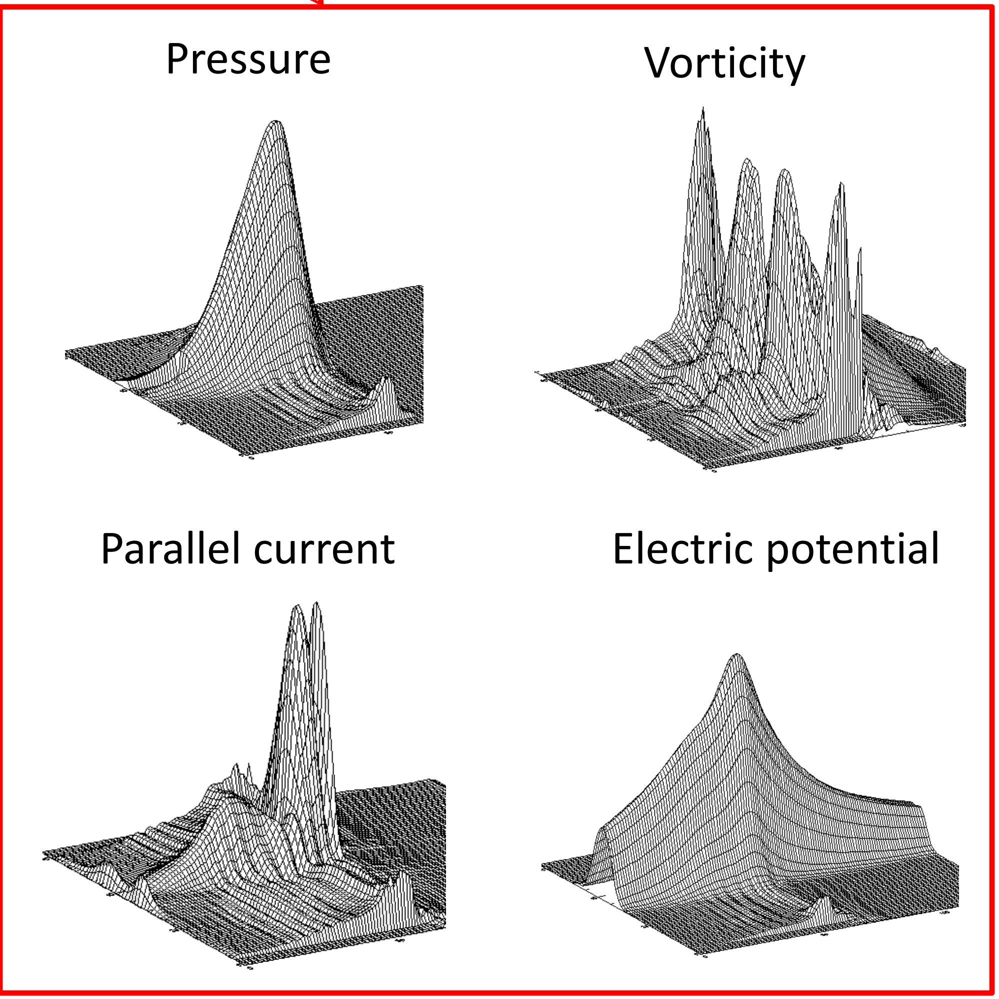
- For ideal P-B mode, growth rate in snowflake divertor is larger than that in Standard divertor.
- Ion diamagnetic effects stabilize P-B mode for moderate and high toroidal mode number.



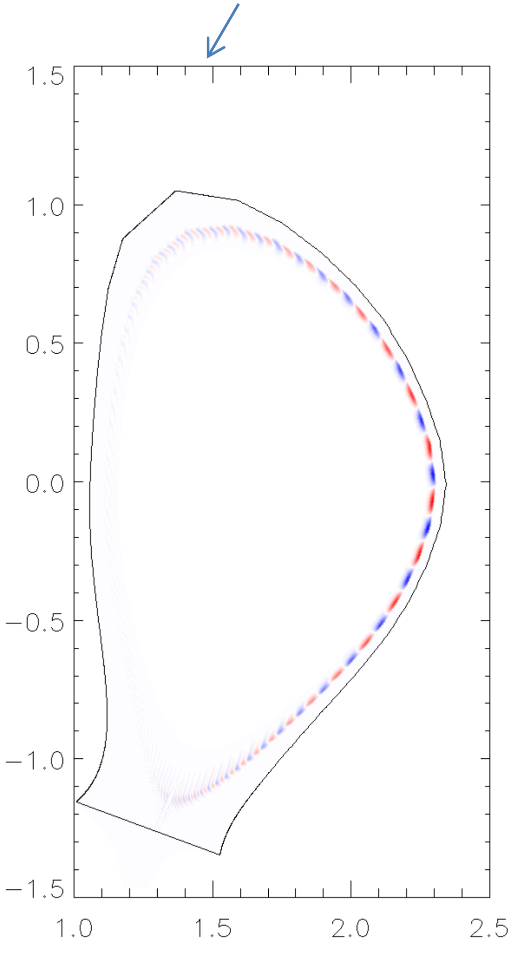
Linear results (mode structure)

All variables are fluctuating parts after root-mean-square (rms) averaging.

N=20, Standard Divertor



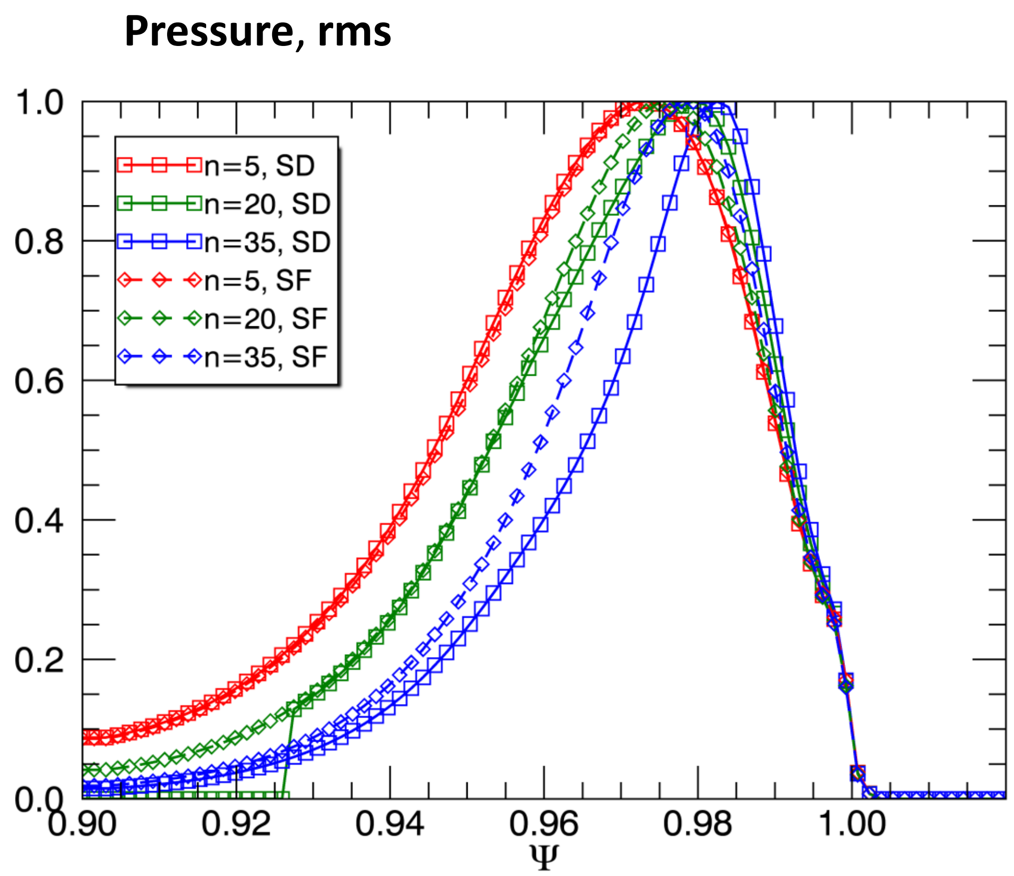
Pressure fluctuation



Radial mode structure, ideal MHD

- The width of radial mode structure increases as toroidal mode number increases for both divertor geometry.

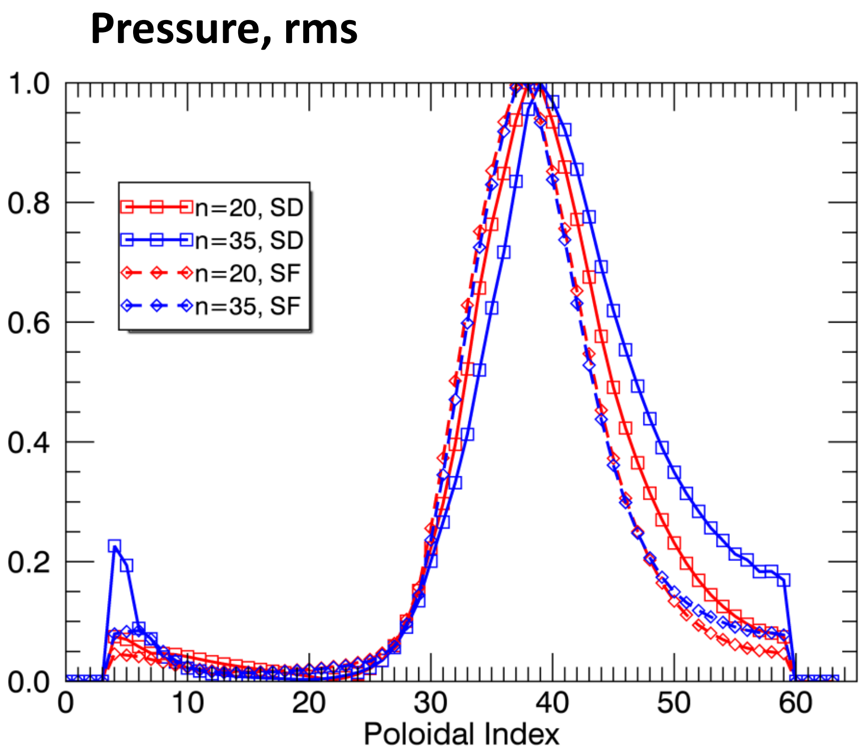
- The radial mode strcuture width in SF geometry is the same as in SD geometry for low toroidal mode number, but larger for moderate and high ones.



Poloidal mode structure, ideal MHD

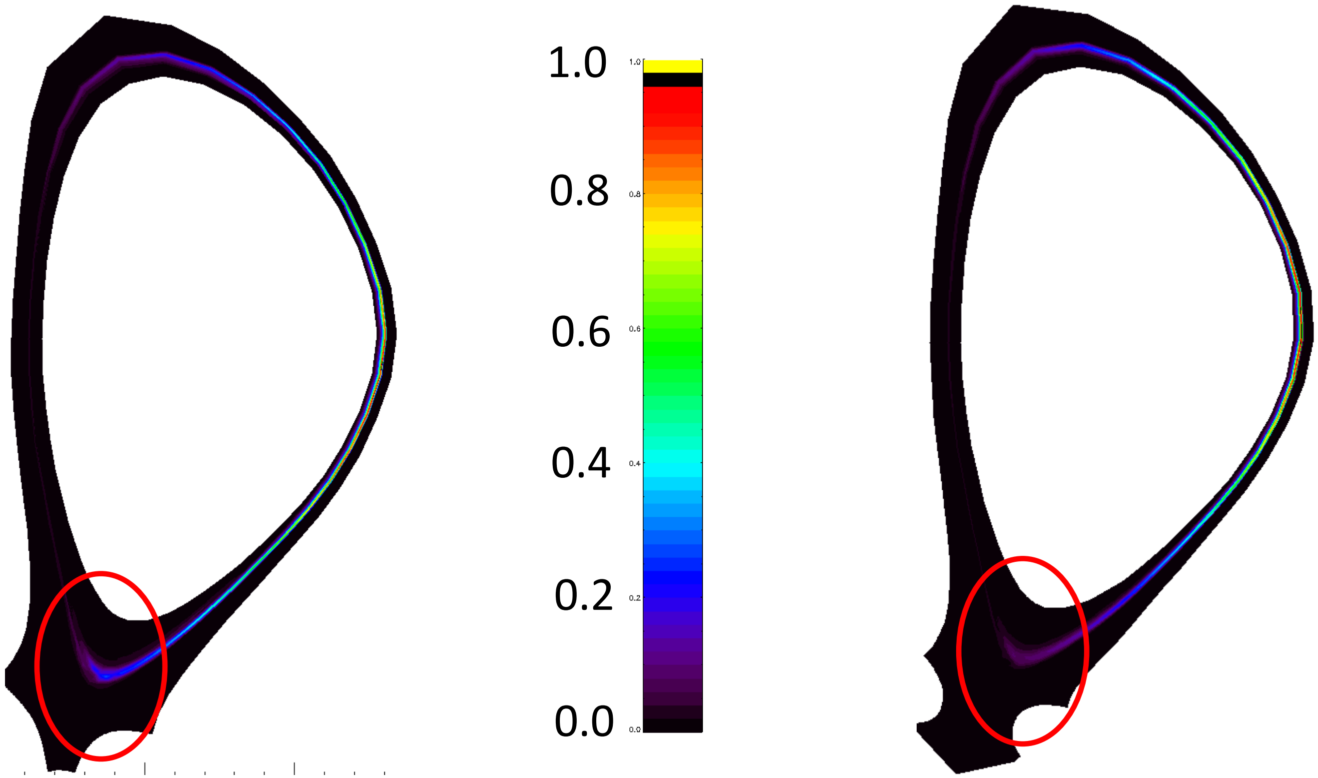
- The width of linear poloidal mode structure increases as toroidal mode number increases in standard divertor geometry, while in snowflake geometry the width stays the same.

- The width of linear poloidal mode structure in snowflake divertor is smaller than in standard.



Poloidal mode structure, ideal MHD

Pressure (rms) contour, n=35



Standard divertor geometry

Snowflake(plus) divertor geometry

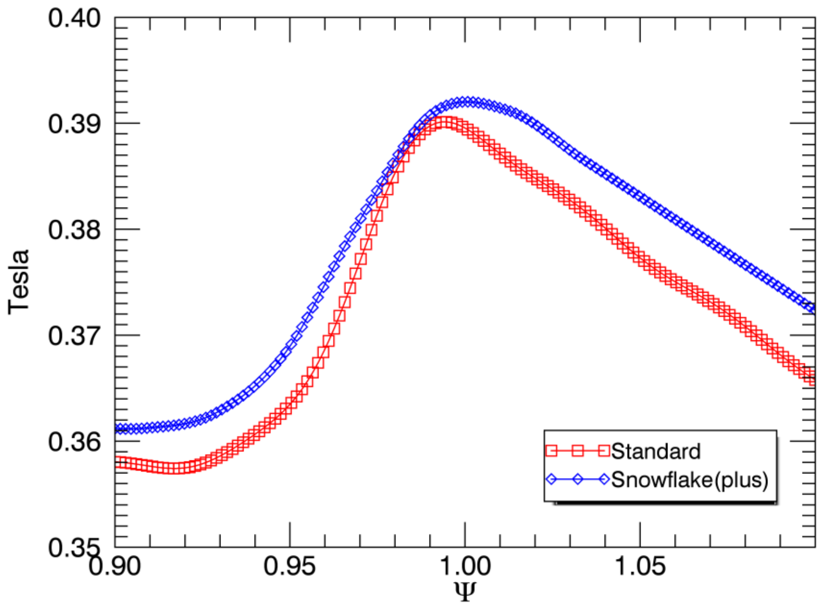
Linear ideal MHD results conclusion

- Mode structure in snowflake (plus) divertor geometry is more radially extended yet less poloidally extended. (More ballooning)
- Linear growth rate in snowflake divertor geometry is larger than in standard.
- Together with these two conclusion, we predict that size of ELM bursts may be larger in snowflake divertor geometry.

Linear ideal MHD results explanation

- As the implementation of snowflake divertor requires additional poloidal field(PF) coils, pedestal characteristics such as curvature, magnetic shear, etc., may be changed, which will results in different linear behavior of peeling-ballooning mode.
- After comparison of different parameters between these two geometries, we found that local magnetic shear plays an important role.

Poloidal magnetic field at out midplane



Local magnetic shear s

Local magnetic shear calculation

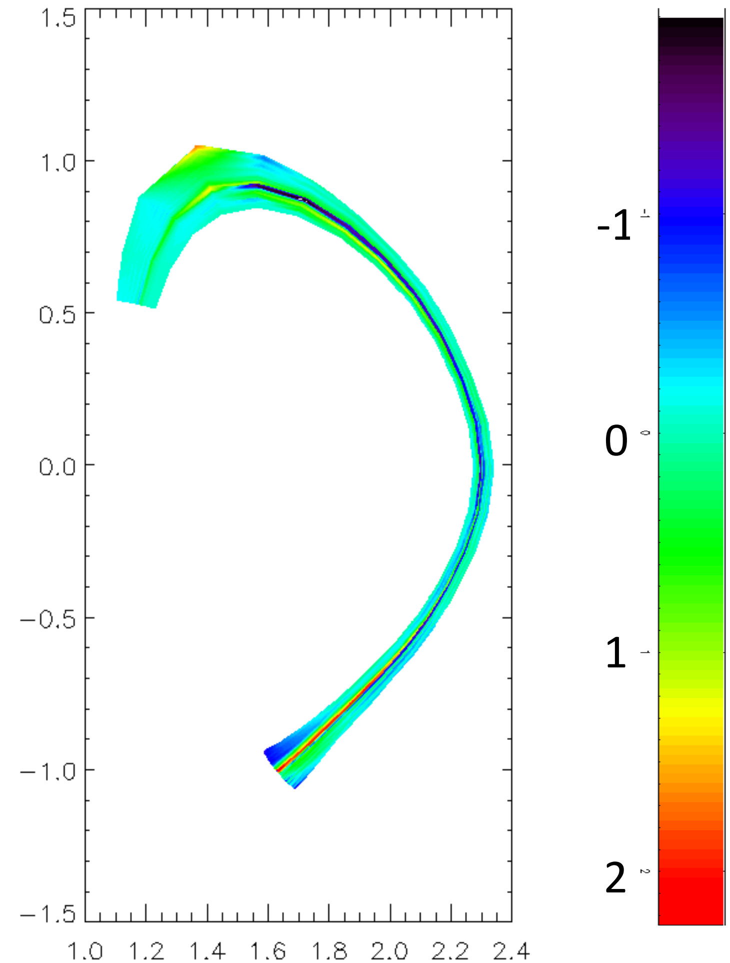
$$r = \sqrt{(rxy - r_0)^2 + (zxy - z_0)^2}$$

$$\nu = \frac{rB_t}{RB_p}$$

$$s = \frac{r}{\nu}\frac{d\nu}{dr}$$

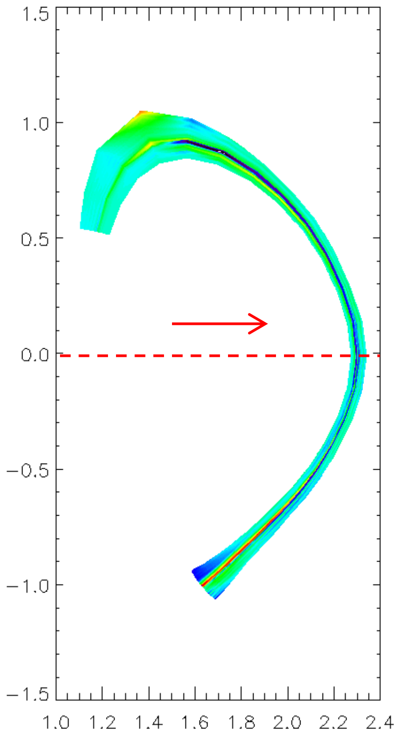
The difference between local shear in standard divertor geometry $|S_{std}|$ and snowflake $|S_{snf}|$

Local shear $|S_{snf}| - |S_{std}|$



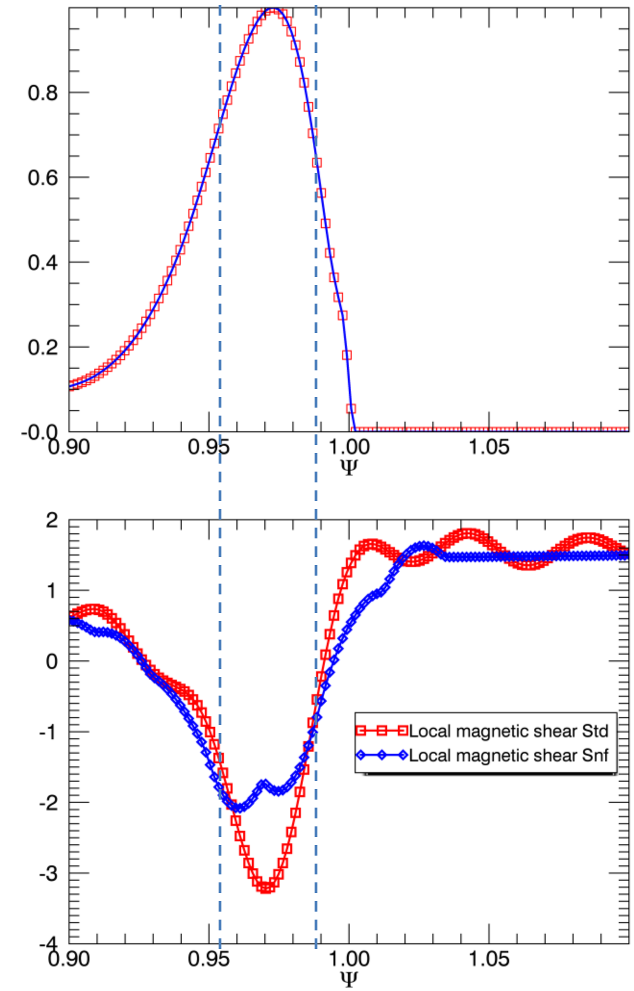
- ➢ Local magnetic shear in snowflake divertor geometry is smaller around out midplane, but larger in other poloidal positions, especially near X-point.

Local magnetic shear s (Radial direction)



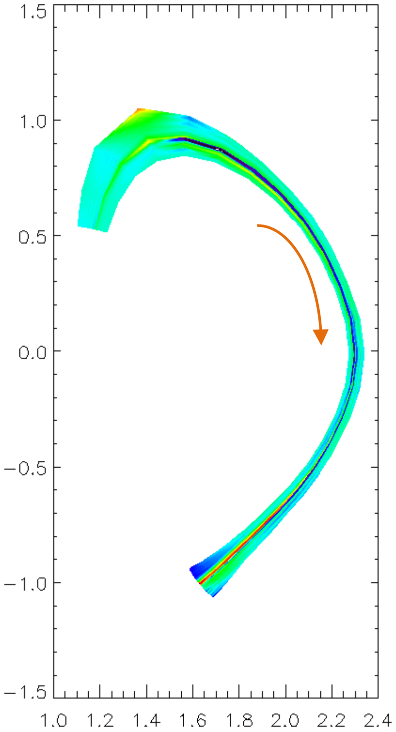
Growth rate and radial mode structure explanation:
At out mid-plane, local magnetic shear in snowflake divertor geometry is smaller (absolute value) at pressure peak gradient radial position, which lead to larger growth Rate and broader radial mode structure.

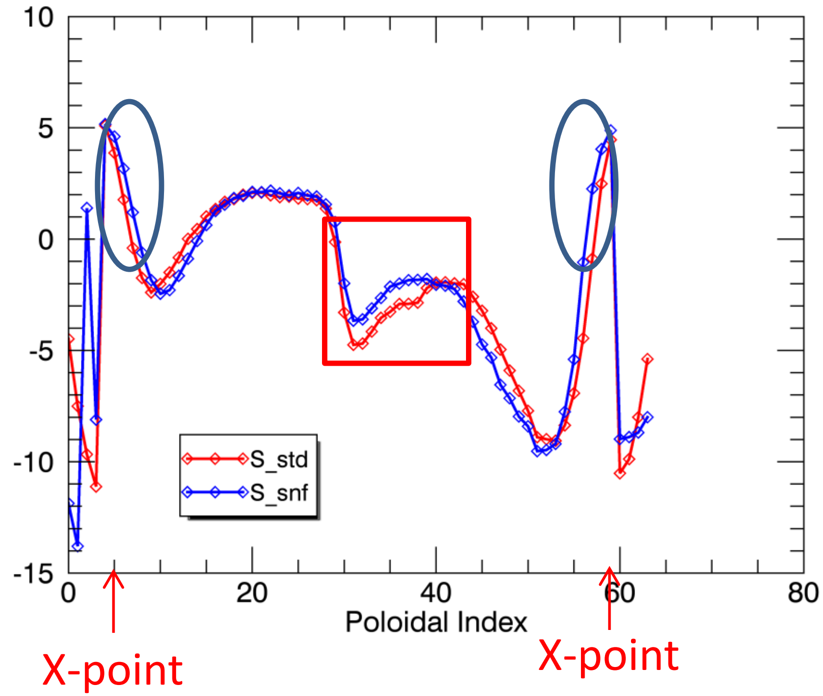
Pressure gradient profile

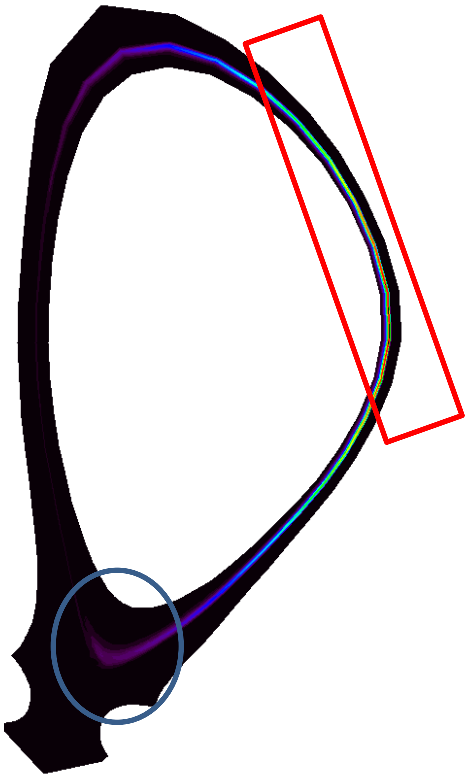


Local magnetic shear in radial direction at out midplane.

Local magnetic shear s (Poloidal direction)







Poloidal mode structure explanation: In poloidal direction, local magnetic shear in snowflake divertor geometry is smaller at out midplane, but larger around X-point. Therefore, poloidal mode structure is more extended in standard divertor geometry.

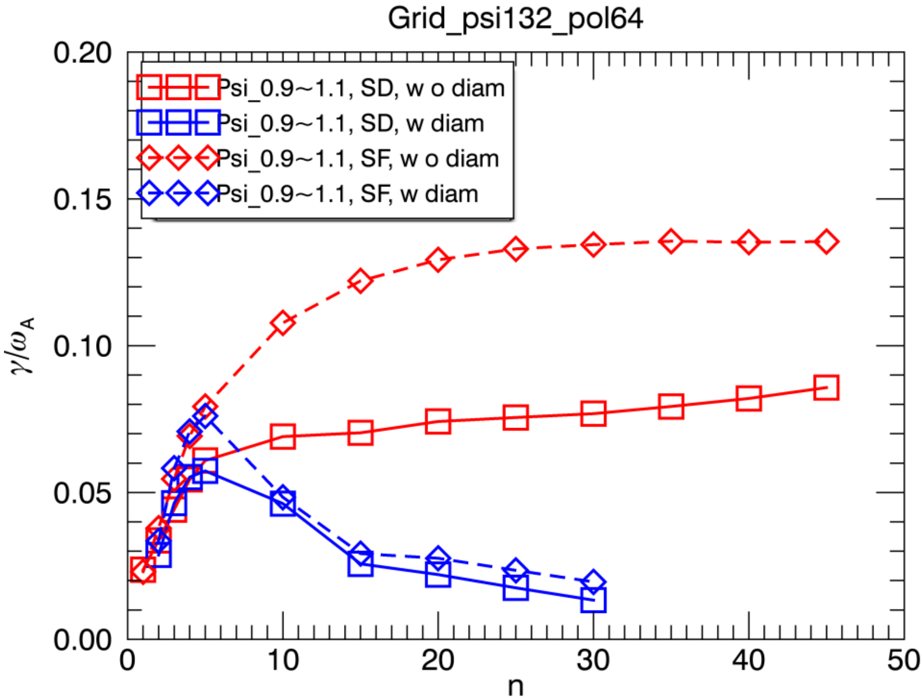
Ion diamagnetic effects

$$\varpi = \frac{n_0 M_i}{B_0}\left(\nabla_\perp^2 \tilde{\phi} + \boxed{\frac{1}{n_0 Z_i e}\nabla_\perp^2 \tilde{p}_i}\right)$$

Ion diamagnetic effects

Equilibrium electric potential Φ_0 is set to balance background flow.

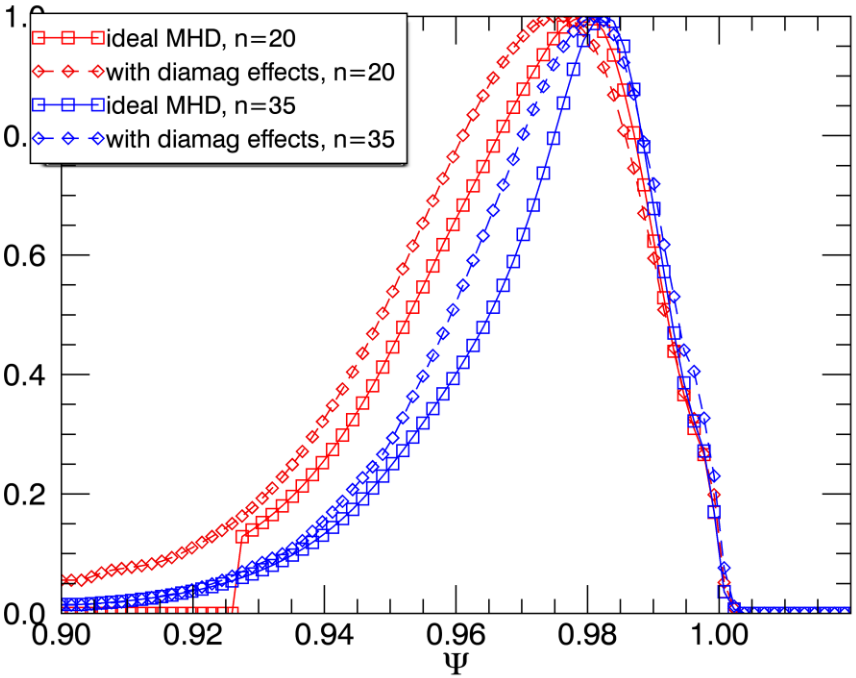
$$\boldsymbol{V}_o = \boldsymbol{V}_{di} + \boldsymbol{V}_{Eo} = \frac{1}{eZ_i n_{i0}}\frac{\boldsymbol{b}_o \times \nabla P_{i0}}{B} + \frac{\boldsymbol{b}_o \times \nabla \Phi_0}{B} = 0$$



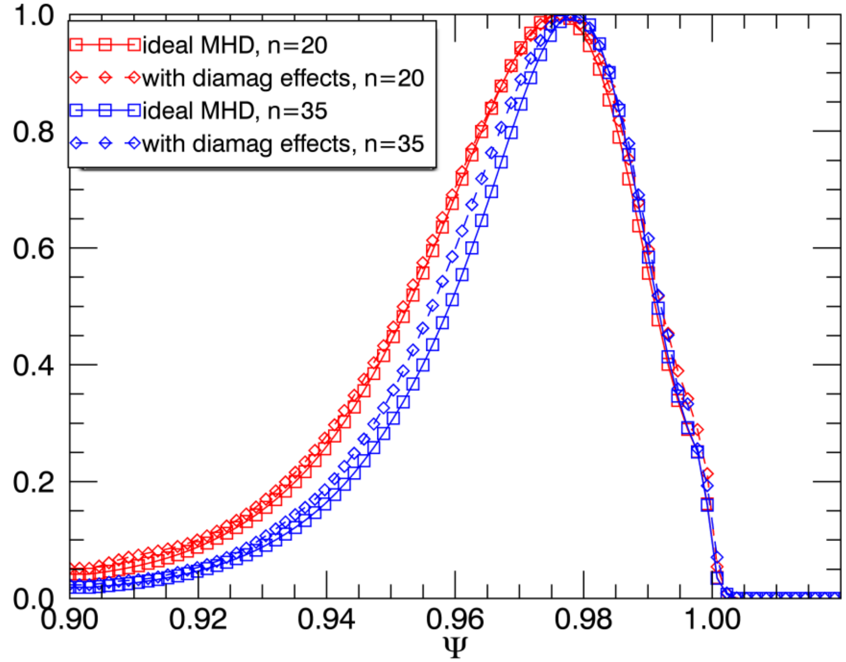
Ion diamagnetic effects are found to stabilize peeling-ballooning mode in pedestal region for moderate and high toroidal mode number, which is consistent with previous simulation results. (Xu et al. 2011)

Ion diamagnetic effects broaden radial mode structure

Standard divertor geometry



Snowflake (Plus) divertor geometry



Conclusion

- The different linear behaviors of peeling-ballooning mode in standard and snowflake (plus) divertor geometry are mainly due to local magnetic shear.
- The additional PF coils in snowflake divertor change the edge magnetic field (primarily poloidal magnetic field) and increase local shear (decrease absolute value) at out midplane, which results in the larger growth rate and wider radial mode structure.
- The local magnetic shear near X-point in snowflake divertor geometry is larger than in standard geometry. Therefore, ballooning mode is suppressed around X-point in snowflake geometry and mode structure is less poloidally extended.
- Ion diamagnetic drift shows stabilizing effects in linear P-B mode growth rate in both geometries. Also, it appears to broaden radial mode structure for P-B mode in both geometries.